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Extremely Red Objects in the Field of QSO 1213–0017: A Galaxy Concentration at $z = 1.31$

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Abstract. We have discovered an excess of extremely red objects (EROs) surrounding the $z = 2.69$ quasar QSO 1213–0017 (UM 485). Optical/IR colors for these galaxies are consistent with $z = 1 - 2$ ellipticals, and there are at least 5 galaxies with spectroscopic redshifts at $z \approx 1.31$. Keck optical spectra for 3 of the red galaxies show rest-frame UV breaks resembling local elliptical galaxies. Our initial results suggest a coherent structure in redshift, possibly arising from a massive galaxy cluster.

1. Introduction

The nature of extremely red objects (EROs) remains an open question in understanding the faint galaxy population at $z > 1$. First identified by Elston et al. (1988), the identity of these objects, defined by their extreme optical/IR colors ($R-K \gtrsim 6$), has proven elusive due to the optical faintness of the population. The few EROs with spectroscopic redshifts form a motley $z \gtrsim 1$ collection, including both ultraluminous dusty star-forming galaxies like HR 10 (Graham & Dey 1996; Dey et al. 1999) and passively-evolving luminous ellipticals like

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LBDS 53W091 (Dunlop et al. 1996). Both of these types of systems are of great utility in learning about the formation of galaxies and clusters of galaxies.

We are conducting an on-going study of EROs, using ground-based optical and near-IR imaging to assemble large samples amenable to statistical studies and Keck optical/near-IR spectroscopy to determine redshifts and physical properties. Deciphering the identity of EROs from broad-band colors alone is ambiguous — spectroscopy is essential. In addition, given the population's apparent heterogeneity, a reasonably large sample of objects needs to be studied to understand the nature and relative abundances of the subsets, instead of the spectroscopy of individual EROs which has been done to date.

We have discovered a concentration of EROs in the field of QSO 1213–0017, a quasar at $z = 2.69$. In this proceedings, we highlight some of our results. The complete analysis and its details are presented in Liu et al. (1999).

2. Optical/IR Imaging: An Excess of EROs

Figure 1 shows optical and IR images obtained from KPNO of the 1213–0017 field. A population of objects with red ($R_S - K > 5$) colors are seen, with the brightest ones being $K \approx 18$. These are as red as the expected appearance of $z \gtrsim 1$ passively evolving ellipticals. Most of the sources are resolved in HST $F814W$ imaging so they are certainly galaxies and not M stars. We also have J and H-band images for a subset of the galaxies; their optical/IR colors are also consistent with $z = 1 - 2$ ellipticals (Liu et al. 1999).

To gauge the significance of these red galaxies, we compare with field ERO counts of Thompson et al. (1999). After accounting for the difference between our R_S filter ($\lambda_c \approx 6930$ Å) and the R_{CADIS} filter of Thompson et al. ($\lambda_c \approx 6480$ Å), we find 4 galaxies with $R - K > 6$ and $K \leq 19$ in the deepest 6.2 arcmin^2 of our images. Compared to the 0.24 objects expected from the field counts, this is a factor of ≈15 excess, with a factor of 6 being the 95% confidence value.

3. Keck Optical Spectroscopy

We identified spectroscopic features for 5 of the 1213–0017 red galaxies (Table 1). Two of them are emission line galaxies. Galaxy R6 shows a single narrow emission line which we identify as [O II] at $z = 1.203$. The spectrum of R7 reveals the presence of an active galactic nucleus, showing strong lines of [O II] and C II] with intrinsic widths of ≈1800 km s^{-1}.

The other 3 red galaxies are devoid of strong emission lines, but they do show continuum breaks identifiable as the rest-frame mid-UV breaks at 2640 Å and 2900 Å (Figure 2). At least two of the red galaxies may also have Mg II in absorption. The UV break features are characteristic of the oldest stellar populations, such as Galactic and M31 globular clusters and the cores of local elliptical galaxies. They have also been identified in high-redshift ellipticals, e.g., LBDS 53W091 at $z = 1.55$. For old stellar populations, this spectral region is expected to be dominated by light from stars near the main sequence turnoff so, in principal, the strengths of these features can be used to infer the age of the population — at least the portion emitting the bulk of the mid-UV flux —

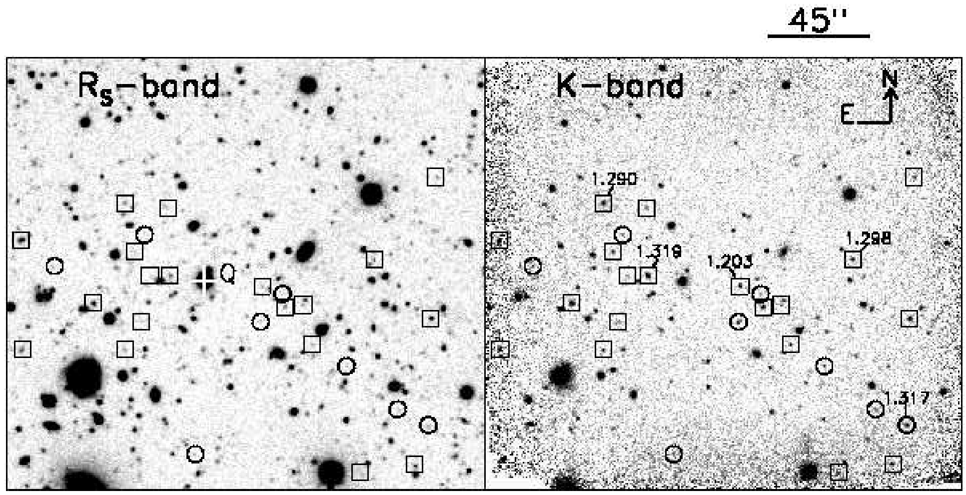

Figure 1. R_S and K-band images of the field. Each is $3\farcm5 \times 3\farcm1$. Objects with $R_S - K > 6$ are circled and those with $R_S - K = 5 - 6$ are marked with a square. The $z = 2.69$ quasar is marked with a white cross and a "Q". Objects with spectroscopic redshifts are labelled by their redshift.

by basically measuring the turnoff mass (e.g., Spinrad et al. 1997). We do not attempt this, but we do point out that real variations exist in the UV colors and spectral break amplitudes of R1, R8, and R10, suggesting heterogeneous stellar populations and star formation histories even though they are at a common location in the Universe and have similar K-band luminosities.

Table 1. Spectroscopic Redshifts in the 1213–0017 Field

Id #	K (mag)	$R_S - K$	morphology[a]	z	spectral features
R1	18.30	6.14	—	1.317	B2640, MgII, B2900
R6	18.89	5.69	diffuse	1.203	[O II]
R7	18.04	5.56	compact+disk?	1.319	[O II], C II], [Ne IV], C III]?
R8	18.94	5.02	—	1.298	B2640, MgII?, B2900, D4000?
R10	18.19	5.98	edge-on disk	1.290	B2640, MgII, B2900, D4000?
Mg II[b]				1.3196	
				1.5534	

[a]As seen in HST $F814W$ images. Sources with a blank line "—" were not observed.
[b]Mg II absorption system in the spectrum of QSO 1213–0017 (Steidel & Sargent 1992).

4. A Coherent Structure at $z = 1.31$

We have found a significant excess of EROs in this field, and of the 5 galaxies with spectroscopic redshifts, 4 lie close together. Moreover, the spectrum of

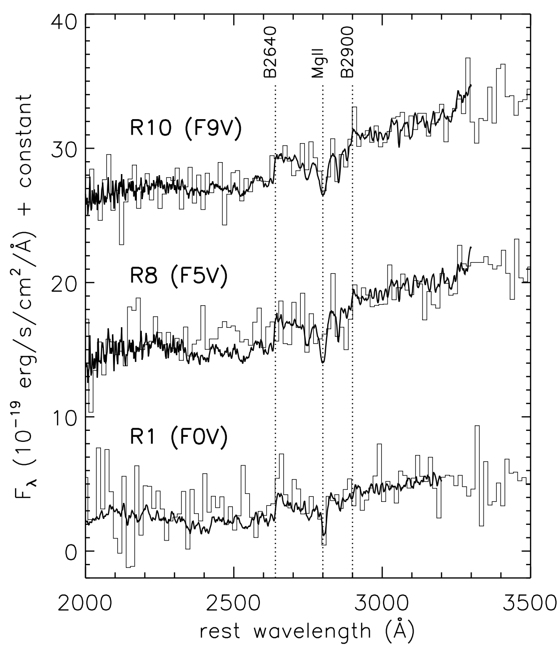

Figure 2. Spectra of the 3 continuum-break galaxies in the 1213–0017 field, averaged in 7 pixel bins. The R8 spectrum is offset by +13 along the y-axis and the R10 spectrum by +26. Overplotted with the thick lines are IUE spectra of F dwarfs, which have been normalized to the galaxy flux longward of 3000 Å.

QSO 1213–0017 shows Mg II absorption at $z = 1.3196$, similar to R7's redshift. It is unlikely that R7 is the absorber as it is 15″ from the QSO (65 h^{-1} kpc for $\Omega = 1, \Lambda = 0$), too large compared to expected sizes of absorbers (Steidel 1993). In addition, our HST images show some faint galaxies closer to the QSO, making them better candidates for the absorber. We therefore have a total of 5 galaxies close in redshift and within $\approx 3\ h^{-1}$ Mpc on the sky. Their unweighted mean redshift is 1.309 with a standard deviation of 1810 ± 580 km s^{-1} and a full range of 3800 km s^{-1} in the mean rest frame.

This is the highest redshift concentration of old, red galaxies published to date which has been spectroscopically confirmed. Further data are needed to gauge if this is a genuine massive cluster, both X-ray images to search for hot intracluster gas in a deep potential and more redshifts to ascertain the velocity distribution. Finally, we point out that galaxies R8 and R10 lie at $z = 1.290 - 1.298$ while the other 3 are at $z = 1.317 - 1.320$, i.e., there is a "gap" of 2500 km s^{-1} in the mean rest frame, though there is no clear segregation on the sky. These may be two separate physical entities (e.g., filaments/sheets/sub-clusters), but this speculation lies beyond the available data.

References

Dey, A. et al. 1999, ApJ, 519, 610

Dunlop, J. et al. 1996, Nature, 381, 581

Elston, R., Rieke, G. H., & Rieke, M. J. 1988, ApJ, 331, L77
Graham, J. R. & Dey, A. 1996, ApJ, 471, 720
Liu, M. C. et al. 1999, in preparation
Spinrad, H. et al. 1997, ApJ, 484, 581
Steidel, C. C. & Sargent, W. L. W. 1992, ApJS, 80, 1
Steidel, C. C. 1993, in The Environment and Evolution of Galaxies, 263
Thompson, D. J. et al. 1999, ApJ, in press (astro-ph/9907216)